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WATER MAIN REPAIR/REPLACEMENT FOR BINGHAMTON, NEW YORK.(U)
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WATER MAIN REPAIR/REPLACEMENT FOR BINGHAMTON, N. Y.

by

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The cost of water main breaks can represent a significant portion of a water distribution system's maintenance costs. While there exists a good deal of qualitative guidance on why pipes break, and when they should be replaced, there are no universal, quantitative rules for determining when to replace pipe. In this study, a model was developed to predict pipe breaks for the Binghamton, N. Y., water distribution system as a function of age, diameter, type, winter temperature, and number of previous breaks. Cost functions were then generated

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20. ABSTRACT (Continued).

for repairing and replacing pipe. Using these functions, guidance on which pipes should be replaced was developed, and costs to maintain the mains for the next 20 years were projected.

It was found that the pipe break rate was not increasing significantly with time indicating that external corrosion was not great. The break rate did show a strong correlation with the severity of the previous winter frosts as indicated by the average temperature in the coldest month. In general, very few pipes in the Binghamton system need to be replaced because of a high break rate.

A pipe should be replaced if its break rate (J) in breaks/year/mile exceeds some critical break rate (J*). The critical break rate (J*) can be given by

$$J^* = \frac{C_r \, 5280 \, L \, \ell n \left(\frac{e^b}{1 + R} \right)}{D\bar{C}_b \left[\left(\frac{e^b}{1 + R} \right)^m - 1 \right]} \qquad \text{for } e^b \neq 1 + R$$

where

J^* = critical break rate, breaks/year/mile

C_r = cost to replace pipe, \$/ft

L = fraction of pipe replaced (i.e. length replaced/total length)

R = interest rate, %

$\bar{C}_b$ = cost to repair a break, \$

D = factor for damage and inconvenience caused by break

m = period of analysis, years

b = slope of break rate vs. age curve on semi-log paper, 1/years

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PREFACE

The U. S. Army Engineer Baltimore District is performing an Urban Water Supply System Study for the City of Binghamton, New York, under Section 214 of the 1965 River and Harbor and Flood Control Act (P.L. 89-298). Baltimore District personnel requested assistance from the U. S. Army Engineer Waterways Experiment Station (WES), under Inter Army Order NABC 80-52.

The work consisted of (1) providing assistance in the pressure analysis of the Ross Park portion of the City of Binghamton water distribution system using the MAPS (Methodology for Areawide Planning Studies) computer program, and (2) conducting a pipe break and replacement analysis of the entire Binghamton system. This report gives the results of the latter task and is essentially the same as the report furnished to the Baltimore District on completion of the study. The report of the former task is to be prepared by Baltimore District personnel.

This work was performed by Dr. Thomas M. Walski, research civil engineer, Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), and Mr. Anthony Pelliccia, civil engineer, Computer Aided Design Group, Automatic Data Processing Center. The report was reviewed by Mr. Paul R. Schroeder of the WREG. The work was conducted with the support of Mr. Robert Pace, economist, Urban Studies Section, Baltimore District. Assistance was also provided by Mr. Don Gay, Mr. Adam Nanni, and Mr. John Linsky of the City of Binghamton.

The work was conducted under the supervision of Dr. Raymond L. Montgomery, Chief, WREG, and Mr. Andrew J. Green, Chief, EED. The Chief of EL was Dr. John Harrison. The Commander and Director and Technical Director of WES were COL Nelson P. Conover and Mr. F. R. Brown, respectively.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609347	kilometres
Fahrenheit degrees*	5/9	Celsius degrees or Kelvins

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

WATER MAIN REPAIR/REPLACEMENT FOR BINGHAMTON, N. Y.

PART I: INTRODUCTION

Background

1. Water distribution systems have a finite life. As pipes age, they lose their carrying capacity and become prone to breaking. There is a time in the life of a pipe after which it is more economical to replace the pipe rather than repair it.

2. Many cities, especially older cities in the Northeast, are currently experiencing the high breakage rates typical of decaying systems. There is very little quantitative guidance available to assist the water utilities in determining precisely when a pipe should be replaced.

3. The distribution system for the City of Binghamton, N. Y., is over one hundred years old, and experiences pipe failures each year. There has been concern over what could be done to upgrade the system at the lowest possible cost. Consequently, under Section 214 of the 1965 *Flood Control Act* (P. L. 89-298), the State of New York requested that the Baltimore District of the Army Corps of Engineers conduct an Urban Water Supply System Study for the City of Binghamton.

4. Baltimore District personnel inventoried all of the mains in the system, especially with regard to the number of pipe failures. They prepared tables on the characteristics of the system using a computer data base and prepared a draft report summarizing the occurrence of breaks for each individual pipe within the system. The report also offered some insight into the probable cause for the higher incidence of breaks (e.g. the higher incidence of breaks due to severe cold weather between the months of November and April, or the higher incidence of breaks for pipes located in heavy traffic areas).

5. Although the report contained a generous amount of descriptive information, more work was required to produce guidance on management

decisions that need to be made on the distribution system. Since information on costs of repair and replacement was not included, the report did not provide adequate guidance on when pipes should be replaced on an economic basis.

6. The Baltimore District in turn requested the U. S. Army Engineer Waterways Experiment Station (WES) to conduct a study to develop guidelines for replacing or repairing pipes, and to project the costs to maintain the integrity of the system.

Objective

7. The objective of this work was to develop and apply a procedure which would enable the technical personnel employed by the City of Binghamton to:

a. Decide whether a pipe should be replaced or repaired.

b. Estimate the expected cost in the case of replacement.

c. Estimate the expected cost in the case of repair.

d. Better understand the nature of pipe breaks in Binghamton.

Approach

8. The basis for deciding whether to repair or replace a pipe was the present worth of costs for repair and replacement. The occurrence of breaks in a pipe was projected and the costs were calculated. These costs were compared with the cost of replacing the pipe. In Part II, a model is developed to predict pipe breaks as a function of pipe age, type of pipe, diameter, occurrence of previous breaks and temperature. The costs of repairing and replacing pipes are presented in Part III. The costs and break prediction model are combined in Part IV to predict when typical pipes of the various material types, sizes and previous break history are to be replaced. Next, another rule was applied to identify the pipes which should be replaced in the near

future. Finally, the costs of repairing main breaks were projected for the next 20 years.

Literature Review

9. Most of the available literature contains qualitative discussions on maintenance of distribution systems, and offers very little quantitative information on costs of repairs and replacement. While many articles were reviewed, none could be used directly to provide quantitative guidance for Binghamton.

10. For instance, the AWWA Task Group 2850-D[1] published a Committee Report on replacement of water distribution mains. This report indicated that the replacement of a pipe might ultimately be dictated by inadequate capacity, adverse effect on water quality, structural inadequacy, and excessive leakage. It further suggested that a system of reporting repairs and the associated cost of such repairs might be a useful tool which would enable a comparison to be made between repair costs and replacement costs. The report did not explicitly answer the question of when to replace pipes.

11. Shamir and Howard[2] developed a forecasting technique, which used the number of breaks in some year t_o , to predict the optimal year in which a pipe should be replaced. However, as attractive as this method may seem, there are some serious problems that limit its use in general studies. The first is that Shamir and Howard assumed the cost of replacement and the cost of repair to be constants, whereas in reality the cost of replacing and repairing a pipe is a function of many variables including diameter, depth of cover, and type of pipe. Secondly, very little data was given to verify their break forecasting equation. Thirdly, their break model was developed for Calgary, Alberta, which has a different soil type and climate. So while their formulation was used in this study, a considerable amount of data was required on the probability of a pipe break and the costs associated with such a break in Binghamton.

12. In Great Britain, the Standing Committee on Water and Sewer

Mains has reported "life expectancies" of pipelines ranging from 40 to 100 years for depreciation and 80 to 120 years as "accepted normal life" for calculating benefits.[3] These values, though, are not necessarily the most economical years to replace the pipe.

13. A report prepared by the New York District Corps of Engineers[4] on the water distribution infrastructure (underground facilities) in Manhattan contains an excellent general discussion on causes and types of main breaks in cast iron pipes. Some of the causes for breaks are soil movement, impact, contact with other structures, temperature, corrosion, improper laying and combinations of all of the above. The report contained a table taken from an earlier study of breaks in New York[5] that showed the wide variation in break rates between cities. The rates varied from 1.29 breaks/mile/year in Houston, Texas, to 0.012 breaks/mile/year in Seattle, Washington. Binghamton's rate of 0.111 breaks/mile/year over the last decade would rank the city roughly in the middle of the 16 major cities surveyed.

14. The Manhattan report[4] study team found that the mains were not wearing out with age. The age of the pipe was only a minor consideration in the main replacement program developed in the report. The report showed that location and prior leakage, which eroded the bedding, were the primary break causing factors.

15. A recent study of pipe breaks conducted in the Cincinnati area by Clark _et al_[6] found that the age of metallic (cast iron and steel as opposed to reinforced concrete) pipes was an important factor in determining the time until the first repair and the number of breaks. This study also found the corrosivity of the soil, pressure in the pipe and land use to be important factors.

16. Morris[7] gives the rule of thumb that if three or more breaks occur per 1000 ft of pipe (15.8 breaks/mile), the pipe should be replaced. Since this was written in a manual, he did not cite the analysis used to derive the rule or mention whether the breaks would occur over the life of the pipe or in one year. Note that for a pipe of less than 333 ft, the rule dictates that the pipe should be replaced if one break occurs.

17. The increase in the rate of pipe breaks with age is generally attributed to corrosion which causes iron to be lost from the pipe. This reduces the strength of the pipe even though the appearance may not change. Romanoff[8][9] and Gerhold[10] reported on the loss of weight and pitting in metallic pipes over a period of years in soil environments. Fitzgerald[11] showed that breaks due to corrosion increase exponentially over the life of a pipe, while breaks due to other causes do not vary with pipe age.

18. The Cast Iron Pipe Research Association (CIPRA)[12] gives five criteria which indicate whether metal pipes will be subject to external corrosion, soil resistivity, pH, redox potential, sulfides and moisture. Appendix A to ANSI/AWWA Standard C105-77[13] presents an evaluation procedure for determining if soil is sufficiently corrosive so as to require protection. In this evaluation, points are assigned depending on the five characteristics given above. A score of ten or more indicates that corrosion protection is required.

19. The pipe break data analyzed by the Baltimore District show that more breaks occur in the winter months. This can be expected since soil in Binghamton is very permeable and winters can be severe resulting in large frost penetration depths. Increased soil movements and increased loads on pipes occur when soil freezes.[12][14] Smith[15] showed that loads on pipe can double when frost penetrates to near the top of the pipe.

20. In discussing replacement criteria for the Los Angeles water system, Lane and Buehring[16] stated that they use a computerized data base to identify groups of pipes with a high probability of deficiencies. Then they base their decisions whether to replace a pipe on a "traditional engineering evaluation" which considers maintenance cost history, condition of soil, condition of streets, hydraulic capacity, water quality and potential for liability. If the problems are capacity and quality problems, they usually rely on relining the pipes.

21. Stacha[17] of the Dallas (Tex.) Water Utility gave similar guidance on pipe replacement. He also noted that safety and customer relations are important subjective factors. He attempted to quantify the

cost of interruptions by assigning an "inconvenience value" based on the number of interruptions due to failures per year. According to his analysis, there is no penalty for the first interruption; $250/interruption for the next two interruptions and $500/interruption for additional interruptions. For example, five breaks would have an inconvenience value of $1500.

PART II: PREDICTION OF BREAKS

22. Using data provided by the Baltimore District, several functions were developed to predict breaks given pipe age, length, diameter, type, and number of previous breaks. The subsections that follow describe the development of these functions. The results of this part are used in Part IV to determine guidance for repairing and replacing pipes and projecting pipe repair costs.

Data Base

23. All of the water mains in the water distribution system for the City of Binghamton, N. Y., were inventoried and the results tabulated in a computer data base by Baltimore District personnel. The data base contained:

(1) pipe record number,
(2) street name,
(3) pipe segment origin and destination node,
(4) pipe diameter,
(5) pipe length,
(6) number of hydrants,
(7) year in which pipe was placed,
(8) pipe material,
(9) month and year in which pipe broke,
(10) type of break,
(11) break location.

24. The data base was sent to the WES where the research was ultimately conducted and where the data were stored on the Boeing Computer Services computer. The data base was modified by the WES so that the year(s) in which a pipe broke or was replaced would appear on the first line of data for that pipe. This eliminated the need to analyze several lines of data for each pipe.

Determination of Significant Parameters

25. Before the break prediction functions could be developed, a set of significant independent parameters that could be correlated with break frequency had to be selected. There were three types of pipe in the distribution system--pit cast iron, sand spun cast iron and ductile iron. The first two types had been in use for many years and there were 398 and 112 breaks reported, respectively. The ductile iron pipe had experienced only a handful of breaks--not enough on which to base a predictive function. There were also only 1.04 miles of ductile iron pipe in the system compared to 37.6 miles of sand spun cast iron and 117.4 miles of pit cast iron (see Table 1). Therefore it was assumed that the ductile iron pipe would not be responsible for a significant number of breaks and it was not considered in the remainder of the analysis. Pipe sizes in the system range from 4 in. to 24 in. The distribution of sizes is shown in Table 1.

26. To determine if pipe size and type were statistically significant in determining break frequency, an analysis of variance test was run for the break frequency data shown in Table 2. Note that some pipe

Table 1

Length of Pipe by Size and Type

	Length, mile		
Diameter in.	Sand Spun Cast Iron	Pit Cast Iron	Ductile Iron
4	0.4	5.9	0.0
6	22.2	60.1	0.25
8	5.7	28.9	0.07
10	0.5	2.0	0.17
12	6.5	15.9	0.55
14	0.3	0.0	0.0
16	1.3	1.7	0.0
18	0.0	0.6	0.0
20	0.5	1.9	0.0
24	0.3	1.1	0.0
	37.7	118.1	1.04

Table 2

Break Frequency by Size/Type

(number/year/mile)

Size (in.)	Pit Cast Iron	Sand Spun Cast Iron
4	0.0577	0.0721
6	0.0376	0.1000
8-10	0.0400	0.0479
12	0.0916	0.1002
14-18	0.0459	0.0943
20	0.2030	0.0810
24	0.3600	0.3161
Overall	0.055	0.088

sizes were grouped together since there were very few breaks or miles of pipe in that category (e.g. no 18 in. diameter sand spun cast iron pipe). The results showed that size was a significant factor at the 5 percent significance level equal to 0.05. It was also found that almost all of the variation due to pipe size was caused by the larger pit cast iron pipe sizes (20 in. and 24 in. diameter) which have a higher incidence of breaks. It was noted that if only the pipe sizes less than 20 in. in diameter were considered during the analysis, pipe size was not significant. Therefore it was concluded that pipe diameter was not a significant variable except for large diameter (20-24 in.) pit cast iron pipe.

27. An analysis of variance test also showed that the pipe type was not significant at $\alpha = 0.05$, but that it was significant at $\alpha = 0.10$. For the purpose of this study it was decided that, since it would be interesting and not especially difficult to develop separate break rate functions for pit and sand spun cast iron, separate functions would be developed even though they were only marginally significant.

28. Another analysis of variance test was conducted to determine if pipes with previous breaks were more likely to break again than pipes without previous breaks. The test showed that the previous break history made a significant difference in the probability of a future break.

29. Note that all of the tests were done in terms of break frequency in breaks/year/mile. For each pipe the number of breaks was counted and divided by the product of the number of years a pipe had been used and the length.

Break Function Development

30. In order to perform the analysis for the optimal year to replace a pipe in Part IV, it was necessary to have an equation that can be used to predict the break rate of the pipe in the future. This equation can be developed by performing a regression analysis of the data on pipe breaks in the system discussed earlier. If the regression equation can reasonably match the historic rate of breaks, it should be able to predict future breaks as well.

31. The predictive equation that proved the most manageable was a correlation of breaks with age and pipe type with correction factors for number of previous breaks, pipe size and severity of the winter. The development of each part of this function is presented in the following sections.

Age-Break Function

32. Shamir and Howard[2] used two equations (linear and exponential) to describe the rate of breaks as a function of time

$$N(t) = N(t_o)e^{A(t-t_o)} \tag{1a}$$

and

$$N(t) = N(t_o) + A(t - t_o) \tag{1b}$$

where

N = number of breaks in year t, breaks/length/time

t_o = base year, time

A = rate constant, breaks/length/time^2 (1/time in 1a)

After considerable testing, it was found that the exponential function fits the trends observed in Binghamton better than the linear function. Therefore, an equation similar to 1a was used except that rather than tying the equation to an arbitrary base year (t_o) , t_o was selected as the year the pipe was installed, so that $(t - t_o)$ becomes the pipe age (t) , $N(t_o)$ becomes a regression coefficient (a) and the equation becomes

$$N(t) = a\ e^{b(t-k)} \tag{2}$$

where

$N(t)$ = break rate at age t , breaks/year/mile

a = regression coefficient, breaks/year/mile

b = regression coefficient, 1/year (A in equation(1a))

t = year

k = year pipe was installed

33. It was originally anticipated that there could be a separate set of regression coefficients (a, b) for each size, previous break history, and type of pipe. Unfortunately, there were not enough observations of breaks to arrive at this large number of coefficients. It was found that there were two different aging rates for pipes depending on the material (pit and sand spun cast iron); therefore, two regression equations were determined.

34. Because there was a large amount of variation in the break rate from one year to the next due to such factors as the severity of the winter, the break rate data were grouped into five-year increments for the regression analysis in order to smooth out the annual variations. Pipes that have been replaced were not included in the analysis. The regression equations which were developed are given below and graphed with the data in Figure 1.

Pit Cast Iron (PCI)

$$N(t) = 0.02577\ e^{0.0207(t-k)} \tag{3a}$$

Sand Spun Cast Iron (CS)

$$N(t) = 0.0627\ e^{0.0137(t-k)} \tag{3b}$$

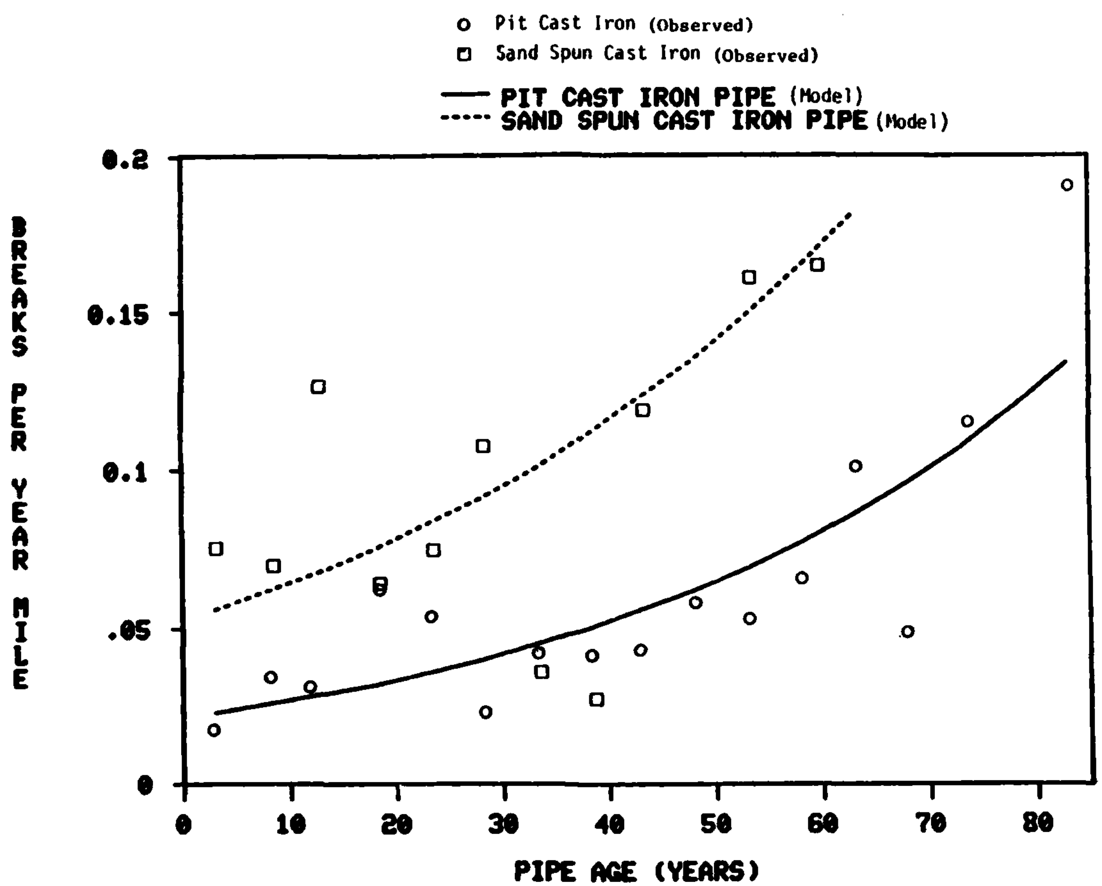

Figure 1. Effect of age on break rate

The index of determination for the pit cast iron pipe was 0.574 and for the sand spun pipe was 0.162. The poor correlation with the sand spun pipe is due to the fact that these pipes experienced high break rates in their early years.

35. The values for b in equation (3) are comparable to the range of values for b of 0.01 - 0.15 determined by Shamir and Howard[2] and 0.08 measured by Clark.[6] The fact that the values for b in equation (3) are on the low end of the range indicate that the break rate is not increasing very quickly with age. This would tend to indicate that the soils in the study area are not highly corrosive. This is consistent with the findings of the Broome County Soil Survey[18] which indicate that the predominant soil is gravely outwash material with low corrosivity. In the hills surrounding the floodplain, there are some Mardin channery silt loams, Lordstown channery silt loam and Chenango and Howard gravely loams with moderate corrosivity and Volusia channery silt loam with moderate to high corrosivity. With the exception of some mains along Park Creek, which are in the Volusia soil, most of the mains in Binghamton are in fairly noncorrosive soils so one would not expect pipes to age quickly (i.e. b will be low).

36. Equation (3) serves as the basis for the break prediction model but does not account for the higher break rates of pipes with previous breaks and of large pit cast iron pipes. Correction factors for these cases are given in the following two sections.

Previous Break Factor

37. A cursory examination of the data indicated that once a pipe broke it was more likely to break again. This was verified by the analysis of variance test. Since there were not enough data to develop individual cost functions (i.e. a's and b's) for pipes with previous breaks, a correction factor (c_1) was developed to modify the overall predicted break frequency for a specific type of pipe. The form of the correction factor is

$$c_1 = \frac{\text{Break Frequency for (pit/sand spun) cast iron with (no/one or more) previous breaks}}{\text{Overall Break Frequency for (pit/sand spun) cast iron}} \quad (4)$$

The data used to calculate c_1 are given in Table 3a and the values for c_1 are given in Table 3b.

Table 3a

Frequency of Breaks (breaks/yr-mile) by Type

Break Occurrence	Sand Spun Cast Iron	Pit Cast Iron
No previous breaks	0.060	0.036
One or more previous breaks	0.824	0.405
Overall	0.088	0.055

Table 3b

Correction Factor (c_1)

Break Occurrence	Sand Spun Cast Iron	Pit Cast Iron
No previous breaks	0.682	0.654
One or more previous breaks	9.36	7.364

Pipe Size Factor

38. Since large pit cast iron pipe exhibited a significantly higher break frequency than smaller pipe, another correction factor (c_2) was required to modify the overall predicted break frequency for pit cast iron pipe to account for pipe size. This correction factor can be given by

$$c_2 = \frac{\text{Break frequency for PCI pipe } (<20/\geq 20) \text{ in diameter}}{\text{Overall break frequency for PCI pipe}} \quad (5)$$

where PCI means pit cast iron. The data used to calculate c_2 are given in Table 4a and the values for c_2 are given in Table 4b.

Table 4a

Frequency of Breaks by Size for Pit Cast Iron Pipes (breaks/yr-mile)

Pipe Size	Frequency
Greater than or equal to 20 in.	0.2596
Less than 20 in.	0.0488
Overall	0.0550

Table 4b

Correction Factors (c_2)

Pipe Size	c_2
Greater than or equal to 20 in.	4.72
Less than 20 in.	0.887

Frost Penetration Effects

39. In order to explain some of the variability in the break rate between years, it was hypothesized that years with large numbers of breaks were characterized by severe winters and hence large frost penetration and increased loads. It was observed by plotting each break in the last 10 years on a distribution map that there were more breaks in pipes in the highly permeable soils in the floodplains of the Susquehanna and Chenango Rivers. While it would have been desirable to

correlate the break rate in a year with maximum frost penetration, such data on frost penetration were not available. The temperature in the coldest month of the year was therefore used as an indicator of the severity of frost penetration.

40. Data on average monthly temperature were obtained from the National Climate Center.[19][20] A table was prepared giving the number of breaks in pit cast iron pipe laid in 1917 vs. temperature and age. A cursory analysis showed that the two years with the highest number of breaks--1934 (14 breaks, 11.4°F) and 1977 (13 breaks, 12.0°F)--were the years with the coldest temperatures. (The average value for average temperature in the coldest month is 21.2°F and the average number of breaks is 3.29.)

41. A multiple regression analysis was performed for the data set for break rate vs. temperature and age. The best-fit exponential and linear equations are

$$N(t\ ,\ T) = 0.0707\ e^{0.0118(t-k)}e^{-0.0305T} \qquad (6a)$$

$$N(t\ ,\ T) = 0.0788 + 0.00086(t - k) - 0.0023T \qquad (6b)$$

where T = average temperature in coldest month, °F. Note that when the average value of T for the study period is entered in equation (6a), it reduces to

$$N(t) = 0.0370\ e^{0.0118(t-k)} \qquad (7)$$

which is reasonably close to equation (3a). The relationship of breaks, temperature and age is shown in Figure 2.

42. A regression of break rate and average temperature in the coldest month yields the following equations

$$N(T) = 0.1740\ e^{-0.0540T} \qquad (8a)$$

and

$$N(T) = 0.135 - 0.00369T \qquad (8b)$$

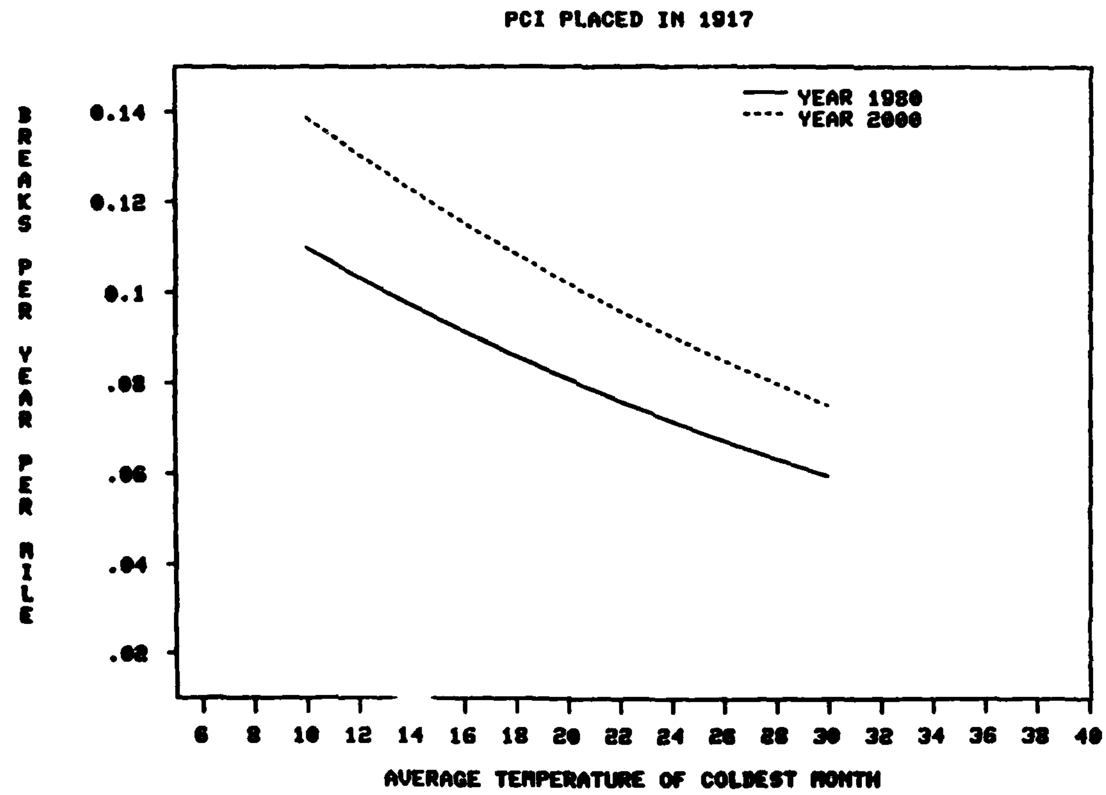

Figure 2. Effect of temperature on break rate

43. The above analysis indicates that the temperature in the coldest month (an indicator of frost penetration) is significant in predicting the break rate. While the effect of frost penetration can be included in an analysis of historic break data, it cannot be used in predicting breaks since it is impossible to predict the severity of a winter before the fact. Equation (3a) will be used to develop replacement guidance instead of equation (6a).

Summary

44. The pipe break prediction model to be used in the remainder of this study can be represented by

$$N(t) = c_1 \, c_2 \, a \, e^{b(t-k)} \tag{9}$$

where

$N(t)$ = break rate at age t , breaks/year/mile

c_1 = correction factor for previous breaks (see Table 3b)

c_2 = correction factor for size (see Table 4b)

a = regression coefficient, breaks/yr/mile

$$= \begin{cases} 0.02577, & \text{for pit cast iron} \\ 0.0627, & \text{for sand spun cast iron} \end{cases}$$

b = regression coefficient

$$= \begin{cases} 0.0207, & \text{for pit cast iron} \\ 0.0137, & \text{for sand spun cast iron} \end{cases}$$

k = year installed

PART III: COST FUNCTION DEVELOPMENT

45. In order to develop an economical management strategy for maintaining the Binghamton distribution system, it is necessary to be able to predict the costs for repairing or replacing water mains. Data on the cost of new pipe are easy to obtain but the cost of repairing a pipe is not generally available in the literature. Shamir and Howard[2] used a replacement cost of $50/ft and a repair cost of $1000/break. These values do not account for the fact that cost varies as a function of pipe size. The following sections give the development of cost functions for Binghamton, N. Y. in which costs are given in June 1980 dollars.

Replacement Cost

46. The City of Binghamton uses ductile iron pipe to replace mains. The WES maintains a computer program, MAPS (Methodology for Areawide Planning Studies),[21] which can calculate costs for various size pipes, given such information as depth of cover, type of pipe and diameter or flow. The program was used to generate costs of ductile iron pipe with 5 ft of cover. The results are given in Table 5.

Table 5

Cost of Ductile Iron Pipe

Diameter (in)	Cost ($/ft)
6	20.8
8	26.4
10	32.0
12	37.0
14	39.4
16	46.6
18	54.2
20	62.2
24	79.1

47. The costs include pipe, installation, excavation, backfill, paving and engineering. The pipe costs were verified in conversation with City of Binghamton Engineering department personnel. Note that 4 in. pipe is not listed since it is to be replaced by 6 in. pipe for the extra carrying capacity.

Repair Costs

48. The costs to repair a pipe are not available from standard sources and therefore had to be synthesized. These cost estimates were generated with the assistance of the City of Binghamton, Water Distribution Department personnel. The cost to repair a main break can be divided into several items:

$$\text{Cost of Repair} = \text{Crew} + \text{Equipment} + \text{Sleeve} + \text{Repaving} + \text{Overhead} \quad (10)$$

The cost of each of these items can be estimated separately. The costs are presented in Table 6.

Table 6

Cost to Repair Main Break

(1980 Dollars)

Diameter (in.)	Crew ($)	Equipment ($)	Sleeve ($)	Repaving ($)	Overhead ($)	Total($\bar{C}_b$) ($)
4	256	45	53	120	95	572
6	290	45	67	120	104	626
8	315	45	77	120	111	668
10	336	45	93	120	119	713
12	356	45	112	144	133	799
14	372	45	239	144	160	960
16	383	45	268	144	168	1008
18	397	45	280	144	173	1039
20	412	45	290	192	188	1127
24	430	45	507	192	235	1409

49. The cost for the crew is the sum of the labor cost for a 3 man crew, plus the cost of a truck for the crew. These costs were estimated at \$27/hour. The number of hours depends on many factors, including pipe size since it takes longer to shut down the system after a large main break. The time to shut down and repair a break can be given by

$$\text{Time} = 6.5 \text{ Diameter}^{0.285} \tag{11}$$

50. The cost for equipment (compressor and backhoe) only varies slightly with the size of the pipe. A cost of \$45 is used for all diameters.

51. The breaks are generally repaired by placing a sleeve around the break. The cost of these sleeves vary depending on their length and the thickness of the pipe as well as the diameter. The costs in Table 6 are based on 12 in. long sleeves for diameters of 12 in. and less, and 16 in. long sleeves for diameters greater than 12 in. It is assumed the sleeves would be the type for older (thick) cast iron pipe.

52. The cost of repaving is based on a unit price of \$2.00 per square foot, and a 12 ft long trench. A 5 ft wide trench is used for 10 in. and smaller pipes. A 6 ft wide trench is used for 12-18 in. pipes and an 8 ft wide trench is used for 20-24 in. pipes.

53. An additional cost of 20 percent is added to the cost of repair to cover supervision and contingencies.

54. The total costs were verified in a telephone conversation with City of Binghamton personnel.

Replacement/Repair Cost Ratio

55. While the costs to repair and replace pipe are changing with time, the ratio of these costs remains fairly constant. Shamir and Howard[2] gave the ratio of the cost to replace 1000 ft of pipe to the cost to repair a break as 50:1. This ratio is dependent on pipe size. The relationship is shown in Table 7. The ratio generally increases with pipe diameter since the cost for new pipe is more highly dependent on pipe diameter than the cost for repairing a break.

Table 7

Cost Ratio

Diameter in	Replacement/Break Ratio ($/1000 ft new pipe)/($/break)
4	36.4
6	33.2
8	39.5
10	44.9
12	46.3
14	41.0
16	46.2
18	52.2
20	55.2
24	56.1

Other Costs

56. The costs presented in Tables 5 and 6 refer only to the costs to actually repair or replace pipe. There are other external costs such as inconvenience, damages, and economic losses caused by loss of service or excavation in the street, loss of water due to leaks, icy conditions due to leaks reaching the road surface, loss of pressure for fire fighting during a break, possible contamination of water during repair, and possible subsidence at break site. In general, consideration of these costs would increase the cost of a break and therefore lower the replacement/break cost ratio. Unfortunately it is virtually impossible to estimate these costs so they will not be explicitly considered in Part IV.

57. Claims for damage caused by breaks can be significant. New York City[4] has paid an average of $421,000/year for damage claims in recent years. Considering that there have been roughly 450 breaks/year in recent years, this implies that the average cost for damages is $940/break. This number is significant in comparison to the cost of actually repairing a break. The claims were over three times as high as the settlement. To account for these other costs, a damage and other cost multiplier factor (D) will be introduced. The cost of a break (C_b)

will be the cost given in Table 6 $(\bar{C}_b)$ times this factor.

$$C_b = D\,\bar{C}_b \tag{12}$$

where

D = damage and other cost multiplier

C_b = overall cost of break, \$/break

$\bar{C}_b$ = cost to repair break, \$/break (Table 6)

When these other costs are ignored $C_b = \bar{C}_b$ and $D = 1$. When these other costs are significant (e.g. 150% of repair cost), D will increase $(D = 2.5)$.

PART IV: GUIDANCE FOR PIPE REPLACEMENT

58. General pipe replacement criteria, developed in Appendix A, are applied to the Binghamton distribution system in this chapter to determine guidance for replacing pipe given the break replacement model of Part II and the cost data developed in Part III. While most pipes in the system will not require replacement in the near future, some bad pipes in the system will require immediate replacement and they are identified using the guidance developed here. Finally, the break prediction model is used to predict the cost of repairing breaks over the next 20 years.

Optimal Replacement Age

59. A rule for determining the optimal age of a pipe when it is to be replaced is derived in Appendix A and is given below

$$t^* - k = \frac{1}{b} \ell n \left[\frac{L\ C_r\ 5280\ \ell n\ (1 + R)}{C_b\ a\ c_1\ c_2} \right] \tag{13}$$

where

- a = regression coefficients in equation (9), break/year/mile
- b = regression coefficients in equation (9), 1/year
- c_1 = correction factor for previous breaks
- c_2 = correction factor for pit cast iron pipe size
- C_b = cost of a break, \$/break
- C_r = cost to replace pipe, \$/ft
- k = year pipe installed, year
- L = fraction of pipe to be replaced (ℓ_r/ℓ)
- R = interest rate
- t^* = optimal year to replace pipe, year

60. The value of t^* was calculated for all of the pipes in the system. This was done for $L = 1$, $R = 0.07125$, C_r and C_b as given in Tables 5 and 6 and a , b , c_1 , c_2 and k as appropriate for

that pipe. It was found that none of the pipes need replacement at present.

61. The sensitivity analysis conducted in Appendix A indicated that the optimal replacement year (t^*) was highly dependent on b (i.e. the rate at which the pipes age). This relationship is shown in Figure 3 for sand spun and pit cast iron with and without previous breaks. (Note that optimal pipe age at replacement $(t^* - k)$ is plotted rather than optimal replacement year (t^*) since the year installed (k) varies throughout the system). Since b was found in Part II to be generally about 0.02, Figure 3 shows that it is not economical to replace either type of pipe before it is at least 100 years old even if it has experienced previous breaks.

62. The pipe segments used in the analysis are generally several hundred feet long. While Figure 3 shows that it is not generally economical to replace entire pipes, it may still be economical to replace sections of the pipe which have experienced a number of breaks. Ductile iron pipe comes in 18 and 20 ft laying lengths, so it may be economical to replace several bad lengths of pipe in an overall sound pipe.

63. The parameter L in equation (13) is the ratio of the length replaced to the total length. Figure 4 shows that as the length replaced decreases (L approaches 0), the optimal replacement time increment (i.e. age of pipe at replacement) decreases. Therefore if only 90 ft of a 900 ft pipe segment is to be replaced, the optimal replacement year decreases from 210 to 95. In the case of pipes with previous breaks, their optimal age at replacement can be decreased until it becomes optimal to replace the pipe today.

64. The analysis in Figure 4 shows that costs to maintain the system can be decreased if bad sections of pipe are identified and replaced. Unfortunately, the data were only available for this study on the basis of large segments (several hundred feet) so it was impossible to identify where replacing short sections could be economical. The City of Binghamton should give this more study. It must also be remembered that the unit price of replacement pipe will be larger for small jobs so the prices in Table 5 should be increased accordingly.

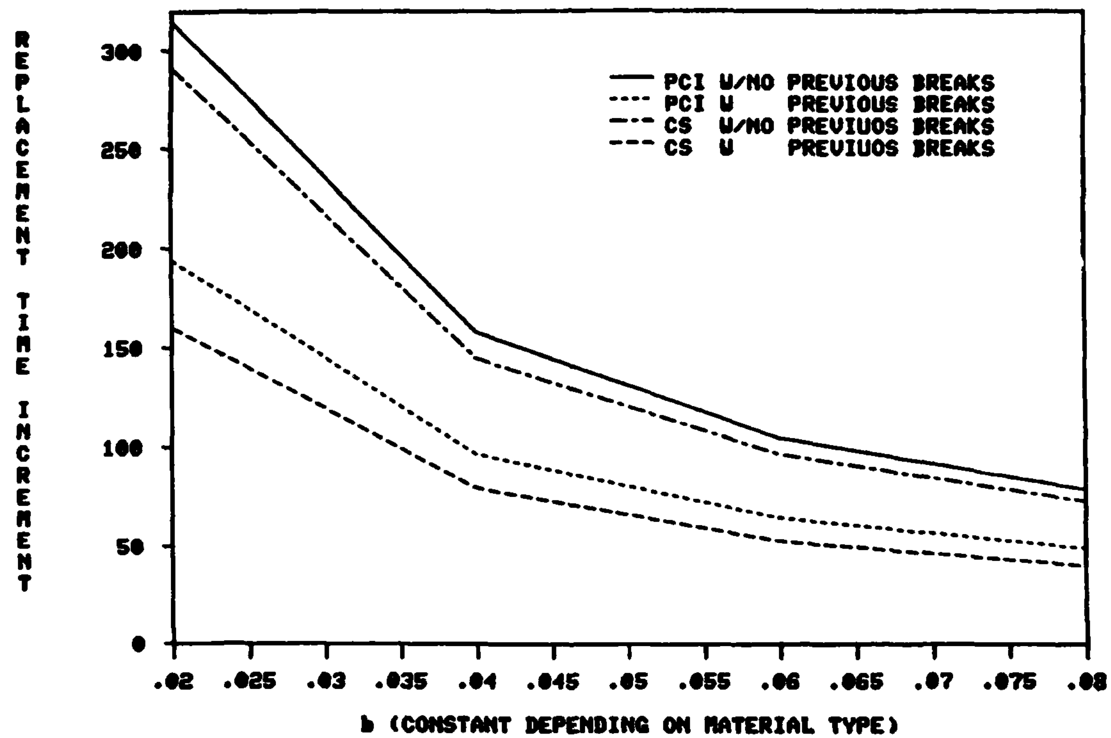

Figure 3. Effect of b and pipe type on optimal replacement age

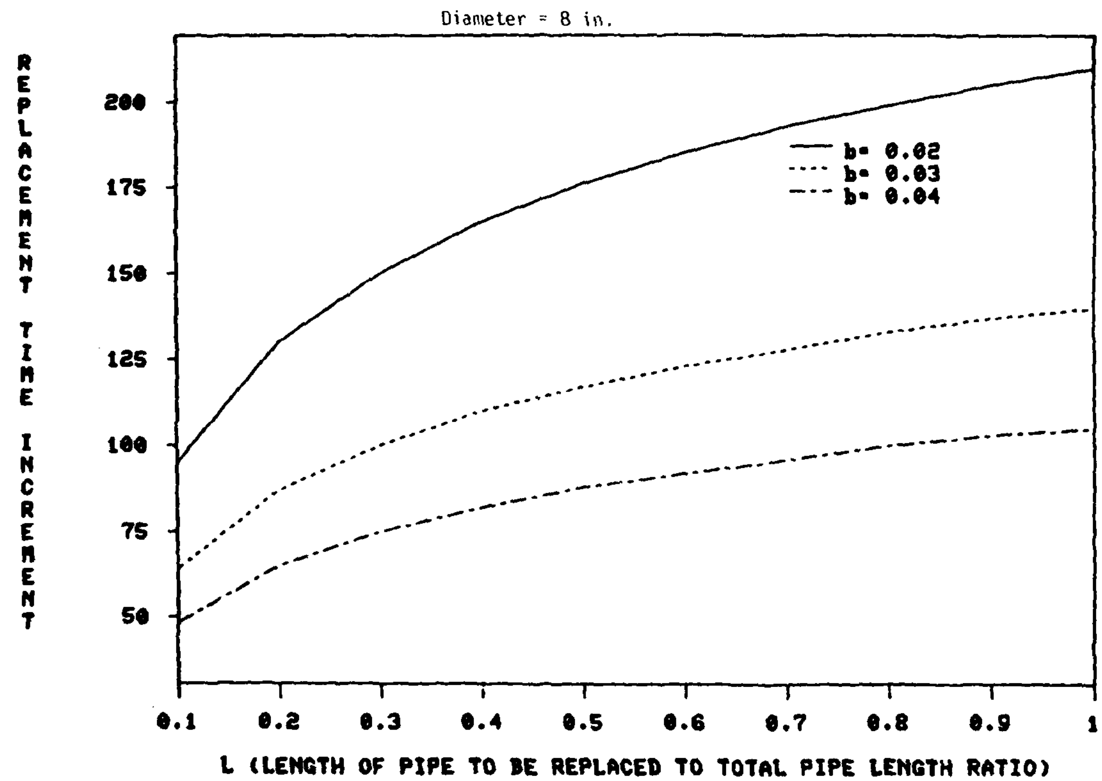

Figure 4. Effect of land b on optimal replacement age

Identification of Bad Pipes

65. The criterion given for pipe replacement in Equation (13) is for pipes with typical values of a and b. It shows that in general it is not economical to replace these "typical" pipes at present unless one only replaces small portions of the pipe. Nevertheless, there are some pipes which due to bad laying conditions, contact with structures, impact or unusually heavy frost or truck loads, have significantly higher break rates (i.e. the values for a and b in equation (9) are too low for these pipes).

66. A criterion to identify these bad pipes is developed in Appendix A. It states that if a pipe's current break rate (J) is greater than some critical break rate (J^*), it should be replaced. This criterion can be represented by

$$J > J^* = \frac{C_r 5280 \; L \; \ln\left(\frac{e^b}{1+R}\right)}{D\bar{C}_b\left[\left(\frac{e^b}{1+R}\right)^m - 1\right]} \tag{14}$$

where

J = current break rate, breaks/year/mile

J^* = critical break rate, break/year/mile

C_r = cost to replace pipe, \$/ft

$C_b = D\bar{C}_b$ = cost of break, \$/break

L = fraction of pipe replaced

b = regression coefficient, 1/years

R = interest rate

m = period of analysis, years

67. Values for J^* depend on the diameter of the pipe, the amount of damage and other costs of a break (D in equation (10)), the period of analysis (m), the amount of pipe to be replaced (L), the rate of increase of breaks (b) and the interest rate (R). Values of

J^* are shown in Table 8. It can be shown that for large values of m (>50), J^* is insensitive to m for $e^b < (1+R)$. Therefore, $m = \infty$ was used $\left[\left(\frac{e^b}{1 + R}\right)^m \rightarrow 0\right]$. Also, for Table 8, $R = 0.07125$, and C_r and $\overline{C}_b$ were taken from Tables 5 and 6. Both replacing only part of the pipe (i.e. decreasing L) and including damages and other costs in the break cost (i.e. increasing D) have the same effect on the critical break rate and therefore, these parameters were lumped together in a dimensionless group (D/L). The effect of increasing this parameter to 5 (e.g. $D = 2$ and $L = 0.4$) is shown in column 4 in Table 8. The effect of increasing D/L to an intermediate value of 2 is given in column 3.

Table 8

Critical Break Rate

Diameter in.	J^* breaks/year/mile $D/L = 1$ J^*_1	$D/L = 2$ J^*_2	$D/L = 5$ J^*_3
4	9.38	4.69	1.88
6	8.56	4.28	1.72
8	10.18	5.09	2.04
10	11.58	5.79	2.32
12	11.90	5.95	2.38
14	10.57	5.28	2.12
16	11.91	5.95	2.38
18	13.46	6.73	2.70
20	14.23	7.11	2.84
24	14.59	7.30	2.92

68. The actual values are presented in Table 9 where they are compared with the critical values. Since breaks in a given pipe are fairly rare events, J was determined by calculating the number of breaks per mile over the last 10 years and dividing by 10. The number of stars associated with pipe segments correspond with the urgency to replace the pipe. Table 9 only includes pipes which have broken at least once in the last 10 years. One star means the pipe should be considered for replacement in the near future; two stars mean it

marginally needs to be replaced now; three stars mean that it urgently needs to be replaced now. The criteria for assigning stars are given below

$$\begin{aligned} &\text{One star} \quad J_3^* \leq J < J_2^* \\ &\text{Two stars} \quad J_2^* \leq J < J_1^* \\ &\text{Three stars} \quad J_1^* \leq J \end{aligned} \tag{15}$$

69. In some cases a fairly short pipe may appear to require replacement using the criteria given above even if has had only one break in the last decade. A dramatic example of this is segment 781 - Conklin Ave which has a break rate of 8.8 breaks/mile/year. The reason for this high rate is not because the segment broke often (it had only 1 break in its life) but rather because it is a very short segment (60 ft). Therefore, the criterion of $J > J^*$ must be tempered by the realization that a single random break event can result in a very high value of J for short pipes. Thus, in additon to the criterion that J be greater than J^* , a pipe should have more than one break in the last decade to be a candidate for replacement.

70. The remaining columns in Table 9 indicate the diameter of the pipe, which is needed to calculate J^* , and other information required to locate the pipe segment on the maps in Appendix C. Column 2 gives the segment number of the pipe and column 3 gives the sector of the map in which the pipe is located.

Maintenance Requirements

71. In addition to being used to identify pipes needing replacement, the pipe break prediction model developed in Part II can also be used to predict the cost of repairing the breaks in the future. For each of the next 20 years, the expected value of the cost to repair a break was calculated based on the pipe material, length, diameter, and previous break history. The sum of the costs in 1980 dollars and in inflated dollars (assuming 12% inflation rate) is given in Table 10.

(Sheet 1 of 3)

Table 9

Identification of Pipes Needing Replacement

Street Name	Segment Number	Map Sector	Diameter (in)	Break Rate (No/mile/yr)	Replacement Priority	Breaks 1970-79
Aldrieda Ave.	400	H4	6	1.8857	*	1
Alfred St.	648	G8	6	1.8857	*	1
Alice St.	1053	D9	8	0.9600		
Altendale Rd.	410	H5	6	2.2957	*	1
Audubon Rd.	326	H3	12	2.1120		
Ayres St.	1588	F4	6	1.7600	*	1
Bedford St.	739	F10	6	1.7600	*	1
Beethoven St.	308	G3	6	1.0560		
Blackstone Ave.	335	H3	6	0.7040		
Broad Ave.	945	D9	12	0.7822		
Brookfield Rd.	406	H5	6	1.6500		
Broome St.	684	E8, F8	6	2.2468	*	2
Broome St.	685	E8	6	0.5280		
Broome St.	1247	E8	24	1.3200		
Campbell Rd.	1577	G4	6	1.3200		
Campbell Rd.	1578	F4	6	1.2279		
Carlton St.	598	G7	4	1.2571		
Chadwick Rd.	385	H4	6	1.32		
Chapin St.	1520	F4	8	0.7543		
Chapin St.	1531	G4	6	1.1733		
Charles St.	1423	D4	6	1.6246		
Chenango St.	1205	E6	10	0.5739		
Circuit	696	F9	6	0.3616		
Circuit	697	G9	16	1.6000		
Cleveland Ave.	40	D1	6	3.1059	*	1
Clifton Blvd.	328	H2	6	0.5558		
Clifton Blvd.	330	G2, H2, H3	6	1.6762		
Clifton Blvd.	332	G2	6	1.0154		
Collier St.	1195	F6	12	1.0560		
Columbia Ave.	549	G6	6	0.6212		
Conklin Ave.	626	F9	8	1.84		
Conklin Ave.	780	F10	6	0.9600		
Conklin Ave.	781	F11	6	8.8000	***	1
Conti Ct.	1385	B6	6	1.2672		
Conti Ct.	1386	B6	6	4.4000	**	5
Court St.	1146	E7	12	0.3641		
Court St.	1147	E7	12	0.6361		
Court St.	1242	E8	12	0.3106		
Court St.	1268	E8, E6	6	0.7543		
Court St.	1270	E6	6	1.3200		
Crary Ave.	80	C2	6	0.7543		
Crestmont Rd.	296	F2	8	0.3911		
Dennison Ave.	1080	B8	6	0.3771		
Devon Blvd.	350	G1	8	0.6600		
Earle Dr.	581	I7, J7	6	0.5867		
East Ave.	821	D11	6	2.2000	*	1
Edgebrook Rd.	377	H4	12	1.0560		
Edgewood Rd.	533	H6, H7	6	0.4800		
Elizabeth St.	1416	D5	6	1.5086		
Ely Pk.	1344	B5	6	0.6400		
Ely Pk	1349	C5	24	1.3200		
Ely Pk.	1387	B4	6	1.41		
Evans St.	652	F8	6	0.4552		

(Continued)

(Sheet 2 of 3)

Table 9 (Continued)

Street Name	Segment Number	Map Sector	Diameter (in)	Break Rate (No/mile/yr)	Replacement Priority	Breaks 1970-79
Evans St.	653	G8	12	1.3200		
Fayette St.	1184	E7	6	1.1733		
Front St.	1301	D6	20	1.6000		
Front St.	1304	D6	8	2.1120	*	1
Front St.	1305	D6	8	5.2800	**	1
Front St.	1328	F5	8	0.3771		
Fuller Hollow Rd.	353	H2	6	0.6600		
Gaines St.	1316	D6	6	0.9962		
Harding Ave.	766	F10	6	0.3520		
Hawley St.	1283	F7, F6	24	0.7040		
High St.	570	G7	6	1.2571		
Homer St.	690	F9	6	1.1234		
Hotchkiss St.	416	I5	6	1.1733		
Howard Ave.	901	E10	8	1.3200		
Howard Ave.	902	D10	4	0.3106		
Howard Ave.	983	C10	6	0.8800		
Iobell St.	1207	F6	8	0.8800		
Julian St.	118	C3	6	0.7135		
Jutland Rd.	340	H2	6	4.17	*	3
Kane Ave.	510	I6	8	1.3200		
Karlada Dr.	1310	C6	6	1.3200		
King Ave.	1530	F4	4	1.3200		
Kneeland Ave.	307	E3	6	1.3200		
Larchmont Rd.	345	G1	8	1.5086		
Larchmont Rd.	346	H2	8	1.2000		
Lathrop Ave.	1554	F4	8	0.8123		
Leroy St.	280	F2	6	1.5086		
Lewis St.	1596	E7	12	0.6212		
Liberty St.	1010	D8	12	2.1120		
Liberty St.	1012	D8	12	2.1120		
Liberty St.	1139	E8	16	2.1120		
Marilyn Ave.	582	J7	6	0.4800		
Mathews St.	92	C2	6	0.9263		
McDonald Ave.	1370	D6	4	0.6600		
McNamara St.	605	G7	6	0.6361		
Mendelsohn St.	180	E3	6	1.1733		
Midwood Dr.	530	H7	6	0.3106		
Mitchell Ave.	484	H6	6	1.2424		
Mitchell Ave.	485	H6	6	1.0154		
Moeller St.	911	B10	6	1.7600		
Moeller St.	987	B10	6	1.2000		
Moffatt	1093	C8	6	0.7881		
Moore Ave.	388	H4	6	1.7600		
Mozart St.	243	E3	6	0.8800		
Otseningo St.	662	F8	6	1.1733		
Park Ave.	82	D2	6	0.5867		
Park Ave.	428	J6	8	0.8800		
Park Terrace Pl.	426	J5	6	1.0776		
Penn Ave.	430	I5	6	1.0058		
Pierce St.	701	G9	6	0.5176		
Riverside Dr.	268	E1	6	1.7600		
Rossmore Pl.	830	E12	6	0.7543		
Rotary Ave.	285	E3, F3	6	1.7600		

(Continued)

Table 9 (Concluded)

Street Name	Segment Number	Map Sector	Diameter (in)	Break Rate (No/mile/yr)	Replacement Priority	Breaks 1970-79
Rugby Pl.	207	D2	6	1.7600		
Rutherford St.	1155	E7	4	1.3200		
Saratoga Rd.	778	F10	12	1.2424		
Sherwood Ave.	515	I7	6	0.8800		
S. Washington St.	466	H6, I6	12	1.1733		
S. Washington St.	467	H6	12	1.2000		
S. Washington St.	470	G6	12	1.7600		
Spring St.	585	I7	6	1.7600		
Spurr Ave.	520	I6	6	0.7543		
St. John Ave.	1514	F4	4	1.9556	*	1
State St.	1198	E6	12	0.7543		
State St.	1199	E6	6	2.2956	*	4
State St.	1200	D6	8	0.6212		
Stone St.	479	G6	6	1.4270		
Sumner Ave.	38	D1	6	3.9112	*	2
Sumner Ave.	39	D1	6	1.7600		
Tompkins St.	658	F8	12	3.5200	*	2
Vermont Ave.	1568	G4	6	1.3200		
Vestal Ave.	312	F1	8	1.1733		
Vestal Ave.	315	G2	8	0.3106		
Vestal Ave.	357	H2	12	0.7543		
Vestal Ave.	359	H4	8	1.76		
Vestal Ave.	362	G5	8	0.8800		
Vestal Ave.	363	G5	12	3.0172	*	2
Vestal Ave.	364	G5	12	1.5529		
Vestal Ave.	371	G7	12	4.4000	*	2
Vestal Ave.	375	G6	6	1.2279		
vestal Ave.	603	G7	12	1.7600		
Walnut St.	1448	E4	6	0.6212		
Walnut St.	1449	F4	6	1.9556	*	1
Walter Ave.	1030	D8	6	0.4673		
Washington St.	1208	F6	10	0.7543		
Washington St.	1210	E6, F6	10	2.11		
Water St.	1218	E6	6	0.7543		
Water St.	1219	D6	8	0.3771		
Webster Court	1245	E9	6	0.7040		
West St.	1233	D7	6	0.4591		
Winding Way	1363	D6	6	1.3200		
Woodland Ave.	586	I7	8	0.4552		

Table 10

Projected Cost to Repair Breaks

Year	Cost in 1980 dollars	Cost in inflated dollars (at 12% inflation)
1981	88,500	99,100
1982	90,300	113,300
1983	92,100	129,400
1984	94,000	147,900
1985	95,900	169,000
1986	97,900	193,200
1987	99,900	220,800
1988	101,900	252,300
1989	104,000	288,400
1990	106,100	329,500
1991	108,200	376,400
1992	110,400	430,100
1993	112,700	491,800
1994	115,000	562,000
1995	117,300	642,000
1996	119,700	733,800
1997	122,200	839,000
1998	124,700	958,900
1999	127,200	1,095,000
2000	129,800	1,252,000

72. Table 10 shows that as the system ages, the pipe break rate and break repair costs will steadily increase. Assuming a value for b of 0.02, the costs will double every 34.5 years if inflation is ignored. Including inflation the doubling time will be greatly reduced.

73. Table 10 is based on winters of average frost penetration. The actual cost in future years will depend highly on the severity of the winter. For example, the cost in 1985 is predicted to be $95,900, based on a coldest average monthly temperature of 21.2°F. If the coldest month in a winter was to be 11.4°F (as in 1934), the costs would rise to $131,000 according to equation (6a). If the coldest month was to be 32.4°F (as in 1949), the cost would drop to $69,000.

74. A much more detailed version of Table 10 is contained in Appendix B. In this appendix, the expected value of repair costs for each pipe is presented for each year from 1981 through 2000. Note that the expected value of a break is the product of the probability and the cost to repair a break. Therefore, the annual costs to repair a main appear very low, especially if it will probably break only once every 50 years (e.g. if probability of break is 0.02 and cost is $500, cost is $10/year). Appendix B contains the street name, pipe segment number and beginning and ending node numbers so that the pipe can be identified in the maps in Appendix C.

75. The costs in Table 10 were developed with the assumption that no pipes will be replaced. If a pipe is replaced, the costs will be reduced each year by the amounts given in Appendix B for that pipe.

PART V: SUMMARY AND RECOMMENDATIONS

Summary

76. Pipes break due to a large number of reasons including improper laying, impact, contact with other structures, frost loads, soil movement, corrosion, freezing and combinations of the above. Because of the correlation of number of breaks and winter temperatures, it can be concluded that frost loads on pipes have a significant effect on break rates in Binghamton. The relatively low value for the rate of change of the break rate indicates that corrosion is not a severe problem in Binghamton.

77. A set of equations was developed in the report to predict the rate of breaks of pipes depending on their diameter, age, material, temperature and previous break history. While the equations describe the break rate for typical pipes, there is considerable variation in the breakage rate between different segments of pipes.

78. Given typical labor and equipment requirements, data were synthesized to predict the cost of repairing a break as a function of pipe diameter. The true cost of a break should also include an estimate of damages and inconvenience.

79. Based on an economic analysis, it is possible to predict when typical pipes should be replaced. Using a similar analysis, it is possible to identify pipes needing immediate replacement.

80. The decision if and when to replace a pipe depends on the cost of a break (C_b), the price of replacement pipe (C_r), the total length of the pipe (ℓ), the length of pipe to be replaced (ℓ_r), the pipe diameter (c_2), the previous break history (c_1), the interest rate (R), the type of pipe (a, b) and the rate at which the pipe is aging (b). The decision to replace pipe is most sensitive to changes in ℓ_r/ℓ and b.

81. The City of Binghamton spends at present roughly $35,000/year to repair mains. Ignoring inflation, this value is expected to double in the next 35 years.

Recommendations

82. In general it is not economically justifiable to replace many pipes simply because of their break rates, although some replacement may be needed to provide additional carrying capacity. Some bad pipes were identified in Table 10. These pipes should be replaced in the near future.

83. In some cases in which pipe replacement is only marginally justifiable, it may be more cost effective to replace small sections of bad pipe if these sections can be identified.

84. Replacement pipe should be designed to withstand loads caused by frost penetration in Binghamton's permeable soils.

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APPENDIX A: DEVELOPMENT OF PIPE REPLACEMENT CRITERIA

1. To develop a rule for determining when to replace a pipe, it was necessary to calculate the present worth of all future pipe replacement and repair costs for every year in which the pipe can be replaced. From these calculations a relationship between total cost and year replaced can be developed, and the replacement year can be selected to minimize total cost. To simplify this analysis, a general formula was developed to calculate optimal replacement year. A sensitivity analysis of the optimal replacement year is then presented. Finally, criteria were developed to identify bad pipe which should be replaced immediately.

Total Cost Function

2. The total cost function is the sum of the present worth of all repair and replacement costs. The present worth of replacement costs can be given by

$$\text{Replacement} = \frac{\ell_r \, C_r}{(1 + R)^{t-j}} \tag{A1}$$

where

ℓ_r = length of pipe to be replaced, ft

C_r = cost to replace pipe, \$/ft

R = interest rate

t = replacement year

j = base year for present worth

The repair cost is the sum of the present worth of the expected value of all repair costs up to and including year t

$$\text{Repair} = \sum_{i=k+1}^{t} \frac{\ell \, K \, e^{b(i-k)} \, C_b}{(1 + R)^{i-j} \, 5280} \tag{A2}$$

where

ℓ = total length of pipe, ft

K = a c_1 c_2, breaks/mile/year

C_b = cost of break, \$

k = year installed

3. The present worth of all costs P(t) is the sum of the costs given in equations (A1) and (A2)

$$P(t) = \frac{\ell_r C_r}{(1 + R)^{t-j}} + \frac{\ell K C_b}{5280} \sum_{i=k+1}^{t} \frac{e^{b(i-k)}}{(1 + R)^{i-j}} \tag{A3}$$

where P(t) = total cost when replaced in year t . Equation (A3) can be made into a continuous function by using very small time steps in calculating cost for repair

$$P(t) = \frac{\ell_r C_r}{(1 + R)^{t-j}} + \frac{\ell K C_b}{5280} \int_k^t \frac{e^{b(u-k)}}{(1 + R)^{u-j}} \, du \tag{A4}$$

Equation (A4) can be differentiated with respect to t to give

$$\frac{dP}{dt} = \frac{\ell K C_b}{5280} \frac{e^{b(t-k)}}{(1 + R)^{t-j}} - \frac{\ell_r C_r \ln (1 + R)}{(1 + R)^{t-j}} \tag{A5}$$

The pipe age (t* - k) which minimizes equation (A4) and hence is the optimal year in which to replace the pipe can be determined by setting the derivative in equation (A5) to zero and solving for t . This solution can be written as

$$t^* - k = \frac{1}{b} \ln \left[\frac{L C_r \, 5280 \ln (1 + R)}{C_b K} \right] \tag{A6}$$

where

t* = optimal year to replace pipe

L = ℓ_r/ℓ = fraction of pipe length replaced

Equation (A6) agrees with the rule developed by Shamir and Howard[2] except that it is based on the year the pipe was installed (k) instead of an arbitrary base year and the costs C_r and C_b are dependent on pipe diameter. Equation (A6) was used in Part IV to calculate the year in which typical pipes of each size, material and previous break history are to be replaced.

Sensitivity Analysis

4. It is possible to calculate the sensitivity of the optimal replacement age to a given variable by taking the partial derivative of equation (A6) with respect to that variable as done by Shamir and Howard. These derivatives are

$$\frac{\partial(t^* - k)}{\partial b} = - \frac{1}{b^2} \ln \left[\frac{L\ C_r\ 5280\ \ln\ (1 + R)}{C_b\ K} \right] \tag{A7a}$$

$$\frac{\partial(t^* - k)}{\partial K} = - \frac{1}{Kb} \tag{A7b}$$

$$\frac{\partial(t^* - k)}{\partial L} = \frac{1}{bL} \tag{A7c}$$

$$\frac{\partial(t^* - k)}{\partial(C_r/C_b)} = \frac{C_b}{bC_r} \tag{A7d}$$

$$\frac{\partial(t^* - k)}{\partial R} = \frac{1}{b(1 + R)\ln(1 + R)} \tag{A7e}$$

The sensitivity can be determined by substituting typical values of the parameters into the appropriate form of equation (A7). For example, suppose the cost of repairing a break in a 12 in. pipe dropped from \$760 to \$720 because of a new tool (replacement cost = \$37/ft) and that the present optimal replacement age is 120 years. The new replacement age can be calculated as follows:

$$(t^* - k) = 120 + \frac{\partial(t^* - k)}{\partial(C_r/C_b)} \Delta\ (C_r/C_b) \tag{A8}$$

$$\Delta\ (C_r/C_b) = \frac{760}{37} - \frac{720}{37} = 0.0811 \tag{A9}$$

$$\frac{\partial(t^* - k)}{\partial(C_r/C_b)} = \frac{C_b}{bC_r} = \frac{740}{0.02(37)} = 1000 \qquad \text{(A10)}$$

Substituting equation (A9) and (A10) into equation (A8) gives

$$(t^* - k) = 120 + 0.0811\ (1000) = 201 \text{ years} \qquad \text{(A11)}$$

which indicates that if the cost of replacement decreases, the optimal age to replace will increase.

5. A more important use of sensitivity analysis is as a tool for examining the uncertainty in the optimal replacement year. The parameters a and b were determined by regression analysis and hence some pipes will have higher values and some lower. Depending on which portion of the data base was examined, a was found to range from 0.0128 to 0.0707 and b could vary from 0.0118 to 0.0304. The effect of this variation on the optimal replacement age of 12 in. pit cast iron pipe ($R = 0.07125$, $L = 1$, $C_r/C_b = 0.0487$) for pipes with and without previous breaks is given in Tables A1 and A2. The analysis shows that the uncertainty in a and b can have a significant effect on the optimal year in which a pipe is to be replaced but that this variation is not important since the years are very high.

Table A1

Sensitivity of Optimal Replacement Age to a and b

(No previous breaks)

b \ a	0.0128	0.0258	0.0707
0.0118	654	595	509
0.0207	373	339	290
0.0304	254	231	198

Table A2

Sensitivity of Optimal Replacement

Age to a and b

(Pipes with previous breaks)

b \ a	0.0128	0.0258	0.0707
0.0118	455	389	304
0.0207	259	222	173
0.0304	177	151	118

Identifying Bad Pipes

6. Tables A1 and A2 and Figures 3 and 4 in the text show that it is not economical to replace typical pipes in the system. Nevertheless, it will be economical to replace all or part of some pipes which have had a record of numerous breaks. A rule to identify those pipes based on their present break rate is given in this section. This can be determined by comparing the cost of breaks based on the current break rate (J, current year is j) with the cost of replacing the pipes. The pipe should be replaced if the present worth of the cost of repairing the breaks between year j and $j + m$ is greater than the replacement cost. This can be written

$$P_b = \ell \int_j^{j+m} \frac{C_b J e^{b(t-j)}}{(1 + R)^{t-j}} \, dt > \ell_r C_r \, 5280 \qquad \text{(A12)}$$

where

J = break rate in year j, break/year/mile

m = period of analysis, years

P_b = present worth of breaks, \$

7. The left side of equation (A12) can be simpified to

$$P_b = \ell J C_b \left(\frac{1 + R}{e^b}\right)^j \int_j^{j+m} \left(\frac{e^b}{1 + R}\right)^t dt \qquad \text{(A13)}$$

Equation (A13) can be integrated to give

$$P_b = \frac{J\ell C_b}{\ell n\left(\frac{e^b}{1 + R}\right)} \left[\left(\frac{e^b}{1 + R}\right)^m - 1\right] \text{ for } e^b \neq 1 + R \qquad \text{(A14)}$$

P_b can be substituted into equation (A12) and solved for J to give

$$J > \frac{C_r \; 5280 \; L \; \ell n \left(\frac{e^b}{1 + R}\right)}{C_b\left[\left(\frac{e^b}{1 + R}\right)^m - 1\right]} \qquad \text{(A15)}$$

The relationship given in (A15) was used in Part IV to identify pipes which need immediate replacement. Note that for $e^b/(1 + R) < 1$ (i.e. $b < \ell n \; (1 + R)$), J is not sensitive to m for large m since $(e^b/1 + R)^m$ will approach 0 for large m. For the case in which $b > \ell n \; (1 + R)$, m becomes important because the rate of increase in costs due to increase in pipe breaks is greater than the rate of decrease in present worth of costs due to interest. In this case m will be smaller and the break rate of the new (i.e. replacement) pipe must also be considered. Equation (A12) becomes

$$\ell \int_j^{j+m} \frac{C_b J e^{b(t-j)}}{(1 + R)^{t-j}} dt > \ell_r C_r \; 5280 + \left\{\begin{array}{l}\text{Cost of repair and} \\ \text{eventual replacement} \\ \text{of new pipe}\end{array}\right\} \qquad \text{(A16)}$$

This becomes especially complicated if the new pipe is better than the old pipes so one cannot be certain of its break rate. In many cases, it will be better quality pipe, installed better or provided with additional protection against freezing and corrosion. In Binghamton, it was found that $b < (1 + R)$ so equation (A15) was appropriate for the study.

APPENDIX B: REPAIR COST BY SEGMENT AND YEAR

1. This appendix contains a great deal of data on individual pipes that would not be of interest to most readers of this report. A limited number of copies of this appendix are available and may be obtained by contacting the authors:

U. S. Army Engineer Waterways Experiment Station
ATTN: Thomas M. Walski (WESEE)
P. O. Box 631
Vicksburg, Miss. 39180

Commercial telephone: 601/634-3931
FTS: 542-3931

2. This appendix contains a table giving the expected costs to repair each pipe from the present through the year 2000. The first line for each pipe contains the segment number, street name, node numbers at the beginning and end of the pipe, and total expected cost for the next 20 years. The next two lines contain the expected cost to repair the pipe for each year from 1981 through 2000. For example, segment number 764 is Montour St. from node 777 to 778. The expected cost to maintain the pipe for the next 20 years is $158.12. The costs will grow from $6.45 in 1981 to $9.56 in 2000.

3. The expected cost was calculated by multiplying the predicted break rate from equation 9 by the cost of repair from Table 6 and the length of the segment. This procedure produced results in very low costs for short pipes with a low break rate.

4. The final rows of the table are a year-by-year total of the costs for all pipes. Inflation was ignored and no present worth calculation was made. All numbers in the table are in 1980 dollars.

APPENDIX C: DISTRIBUTION SYSTEM MAPS

Appendix C consists of maps of the water distribution system. These may be obtained from the report authors or the Baltimore District.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Walski, Thomas M
  Water main repair/replacement for Binghamton, N. Y. / by Thomas M. Walski, Anthony Pelliccia. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1981.
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